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16. ABSTRACT

Dendroecological analysis of 258 increment growth cores collected from red spruce, balsam fir, and Fraser fir in central West Virginia and western Virginia indicates marked declines in growth-trend during the past 20 years similar to that reported for spruce and fir in high-elevation forests of the northern Appalachians. Consequently, growth-trend declines of conifers in subalpine forest ecosystems of eastern North America are apparently more widespread than previously realized and might therefore be related to a large-scale change in air quality. The initiation of growth-trend decline was often synchronous with the onset of a major drought, but the growth rates have failed to recover since the late 1960s when the drought ended.

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GROWTH-TREND DECLINES OF SPRUCE AND FIR IN MID-APPALACHIAN SUBALPINE FORESTS

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ADAMS H. S., STEPHENSON S. L., BLASING T. J. and DUVICK D. N. *Growth-trend declines of spruce and fir in mid-Appalachian subalpine forests.* ENVIRONMENTAL AND EXPERIMENTAL BOTANY **25,** 315–325, 1985.—Dendroecological (tree-ring) analysis of 258 increment growth cores collected from red spruce (*Picea rubens* Sarg.), balsam fir [*Abies balsamea* (L.) Mill.], and Fraser fir [*A. fraseri* (Pursh) Poir.] in central West Virginia and western Virginia indicates marked declines in growth-trend during the past 20 years similar to that reported for spruce and fir in high-elevation forests of the northern Appalachians. Consequently, growth-trend declines of conifers in subalpine forest ecosystems of eastern North America are apparently more widespread than previously realized and might therefore be related to a large-scale environmental perturbation such as a change in climate or a regional-scale change in air quality. The initiation of growth-trend decline was often synchronous with the onset of a major drought, but the growth rates have failed to recover since the late 1960s when the drought ended.

INTRODUCTION

RED SPRUCE (*Picea rubens* Sarg.) is the most characteristic species of the subalpine coniferous forests that occupy higher peaks and ridges of the Appalachian system from Maine to Tennessee and North Carolina. Balsam fir [*Abies balsamea* (L.) Mill.] is commonly present as a codominant species in the northern Appalachians, whereas Fraser fir [*A. fraseri* (Pursh) Poir.], a closely related species, has the same role in the south. Dendroecological (tree-ring) data from studies[9,10] recently conducted in the spruce–fir forests of the northern Appalachians indicate that red spruce has shown a pattern of reduced growth rate and increased mortality during the past two decades. A similar pattern of reduced growth rate has been reported for balsam fir,[21] but this does not seem to be accompanied by the high rate of mortality observed for spruce. The exact cause(s) of decline in growth rates for these and other species is still unknown, although acid deposition has been suggested as a possible contributing factor,[9–11,18,19,26] because the affected forests are located in areas receiving high atmospheric inputs of acidic substances and other pollutants.[6,12,15] JOHNSON and SICCAMA[9] have hypothesized that the decline was triggered by a period of drought that occurred in the northeastern United States during the early to mid-1960s. However, quantitative evidence of declining growth rates of spruce and fir in other portions of the Appalachians, which could be used to support or refute this hypothesis, apparently has been lacking. Some authors have contended that spruce and spruce–fir forests in the southern Appalachians appear to be relatively unaffected.[2,9,10] The present study provides quantitative evidence of reduced growth rates for both spruce and fir in mid-Appalachian subalpine forests and further evaluates climatic stress as a possible contributing factor for this decline.

THE STUDY AREA

Spruce and spruce–fir forests are poorly developed in the mid-Appalachians, presumably because few areas in the region reach the elevations necessary to provide the cool, moist environmental conditions required for establishment of this forest type. In central West Virginia and western Virginia, the lower limit of spruce is about 975 m. Balsam fir, reaching its southernmost limit, occurs in only four localities in West Virginia[5] and in just two localities in Virginia.[14] Fraser fir reaches its northernmost limit on Mount Rogers in extreme southwestern Virginia, where nearly pure stands occur at elevations above 1700 m.[23] These mid-Appalachian subalpine coniferous forests have been described by STEPHENSON and CLOVIS[25] and STEPHENSON and ADAMS.[23,24]

Both species of fir included in this study are subject to severe insect infestation (e.g. balsam woolly aphid). Although the balsam woolly aphid has been observed at Mt. Rogers, the trees have not been affected (C. EAGAR, personal communication). There are apparently no records of insect activity on balsam fir in West Virginia; hence, evaluation of any effect from such activity is not possible. Logging activity is known to have occurred in the general study areas where balsam and Fraser fir were cored; however, ages of some trees at these sites pre-date that activity. This would suggest that logging was selective and that these sites may never have been completely logged. Locations and site characteristics of stands from which trees were sampled for the present study are given in Table 1.

MATERIALS AND METHODS

During the 1982 and 1983 field seasons, increment cores were extracted at breast height from a total of 258 spruce and fir trees at 10 different sites in Virginia and West Virginia. Red spruce cores were collected at eight Virginia and two West Virginia sites, balsam fir cores at two sites in West Virginia, and Fraser fir cores at Mount Rogers in southwestern Virginia. Cores were air dried, mounted on grooved boards, and sanded; ring widths (1930–1981) then were measured at Oak Ridge National Laboratory (ORNL), Oak Ridge, Tennessee. Measurements from all cores of

Table 1. Location and summary data for each stand from which spruce and fir core samples were collected

Location	Elevation (m)	Species cored	No. of cores	Mean age and standard error of cored trees (yr)
Highland County, VA	1217	Red spruce	36	68±3.5
Rockingham County, VA	1127	Red spruce	7	144±13.3
Hawksbill Mountain and Limberlost, Shenandoah National Park, VA	1082	Red spruce	7	109±21.2
Clinch Mountain, Tazewell County, VA	1405	Red spruce	17	78±7.8
Salt Pond Mountain, Giles County, VA	1144	Red spruce	24	139±13.0
Clinch Mountain, Russell County, VA	1322	Red spruce	31	58±2.8
Mount Rogers, VA	1726	Red spruce	22	81±7.0
		Fraser fir	22	79±5.6
Whitetop Mountain, VA	1577	Red spruce	21	104±5.5
Randolph and Pocahontas counties, WV	1112	Red spruce	20	86±6.6
		Balsam fir	38	54±1.4
Canaan Valley State Park, WV	980	Red spruce	5	90±9.6
		Balsam fir	8	49±1.4

a single species at each site were grouped and a robust estimate of the mean ring width, or biweight mean, for each year was calculated for that site. The robust mean is less sensitive to values of one or a few outliers than is the simple average because in calculating the robust mean the values are first weighted such that those most distant from the median receive smaller weights, according to criteria given by MOSTELLER and TUKEY.[16] Chronologies then were developed by fitting a spline function[4] to the series of measured values for each core, dividing by the filter value to obtain a series of ring-width indices, and averaging the indices of all cores to derive a site chronology.[4,7] This indexing procedure has been developed over the years by dendroclimatologists as a means of removing natural low-frequency variations (e.g. those due to tree age or to changes in competitive status such as canopy closure) from ring-width series of individual trees before averaging several series into a ring-width chronology. The resulting ring-width chronology represents aspects of ring-width variance that are replicated over several trees and that are not due to the low-frequency natural processes characteristic of individual trees.[4,7] Cubic spline functions have been found to be particularly effective in describing these low-frequency effects.[1,4] In this study we used a spline that described 50% or more of the variance below frequencies of 1 cycle per 60 years. Similar splines have been found to be optimal for describing and removing the low-frequency effects of tree age and stand dynamics from ring-width series of several tree species in the eastern United States.[1,4]

To identify effects of climate on the ring-width chronologies, we used statistical regression to estimate chronology values from corresponding values of climatic variables. To remove effects of climate, these estimated values were subtracted from the corresponding actual values. In practice, it has been found efficient to transform groups of monthly climatic variables into orthogonal principal-component eigenvectors that are then used as predictor variables in regression. This technique of data transformation and regression is called response-function analysis and is discussed in more detail by FRITTS *et al.*[8] Monthly mean temperature and total precipitation for June of the prior year through August of the year of ring formation were used to develop the orthogonal predictor variables in this analysis.

Another way of transforming monthly climatic variables into efficient estimators of tree-ring width is to calculate Palmer drought severity indices (PDSIs)[17] for various times during the growing season. Monthly values of PDSI indicate relative drought conditions for particular local soil characteristics, based on a weighted integral of precipitation and evapotranspiration for several months preceding and including the month for which the index is calculated. The indices may range in value from very dry (≤ -4) to very wet ($\geq +4$), with zero considered normal for any particular region. PDSI values are often highly correlated with tree-ring widths in the eastern United States.[3] Because many reported declines of tree-growth rate in the northeastern United States occurred about the same time as a severe drought in that region, we used the PDSIs to aid in examining drought as a possible contributing factor to the growth-rate declines in our study area.

RESULTS AND DISCUSSION

Increment growth data from cores collected from spruce and/or fir at the four sites with greatest replication (number of specimens) for each species in each state are shown in Fig. 1. Included are pooled data for two sites in Randolph and Pocahontas counties, West Virginia, where cores were taken from red spruce and balsam fir (Figs 1C and D); a single site in Highland County, Virginia where cores were obtained from red spruce (Fig. 1A); and Mount Rogers, the only site in Virginia where cores of Fraser fir could be collected (Fig. 1B). The data presented for these four sites are representative of that obtained at all of the sites we studied. Aggregated increment means and indices for all spruce and all fir from both states are shown in Fig. 2.

A commonly encountered pattern of ring-width decline as the trees grow older is evident in some of the ring-width series. Also evident in all series is an abrupt change in the rate of decline in the 1960s. That change is indicated by a shift to generally lower values of ring-width indices after about 1965 (Figs 2C and D). The mean ring-width indices for the aggregated spruce (Fig. 2C) and

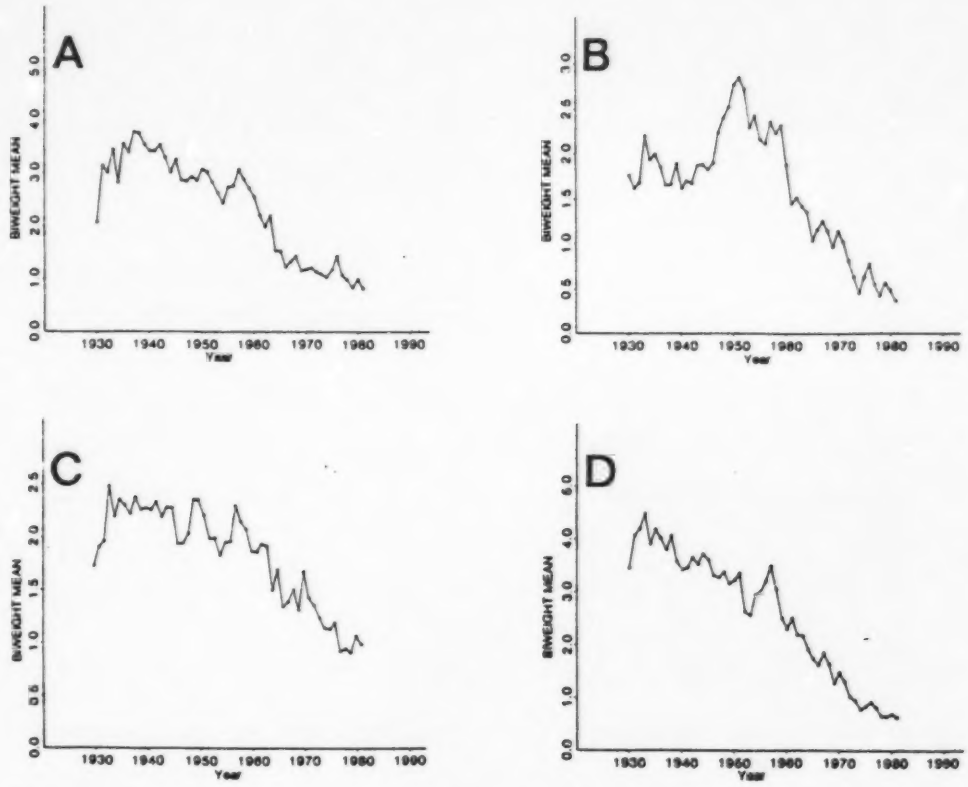

FIG. 1. Mean ring-width series (mm) for tree cores (n = 16–38 ring widths each year). (A) Red spruce in Highland County, VA. (B) Fraser fir at Mount Rogers, VA. (C) Red spruce in Randolph and Pocahontas counties, WV. (D) Balsam fir in Randolph and Pocahontas counties, WV.

the aggregated fir (Fig. 2D) after 1965 were statistically detectable (with 99% confidence) from the mean indices for the same respective chronologies before 1960. The t values, as computed via Statistical Analysis System procedures,[20] were 4.74 for the spruce and 6.02 for the fir.

Occurrence of very narrow rings in recent years for fir is suggestive of the pattern of growth shown by MARCHAND[13] for balsam fir in the dieback zone of 'fir waves.' Such cyclic waves are characteristic of nearly pure fir forests located at high elevations in the northeastern United States.[22] Existence of fir waves in the southern and mid-Appalachians has not been documented and although dominated by fir, our sites had a considerable admixture of other species. Further, there was no evidence of systematic or cyclic dieback in stands we sampled. Therefore, the abrupt change in growth rate of fir in our study cannot be attributed to this phenomenon.

The marked declines in ring-width increment show no indication of recovering. Inspection of individual cores revealed that the decrease in ring-widths usually was rather abrupt and that appearance of the first unusually narrow incre-

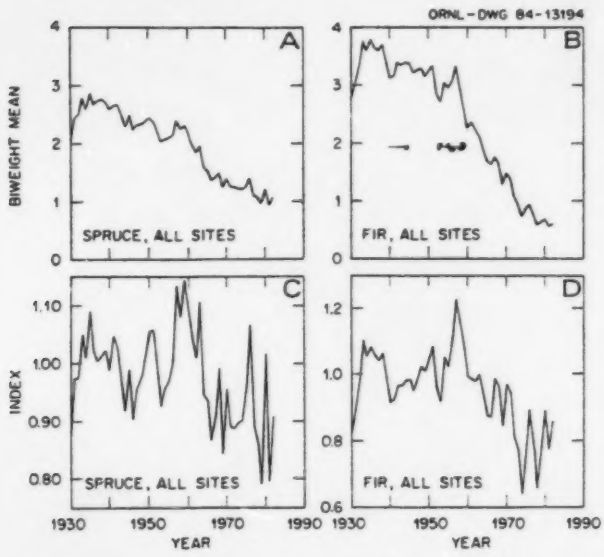

FIG. 2. Mean ring-width series for all spruce (A) and all fir (B) sampled in this study, and their corresponding ring-width indices (C and D, respectively). Ring widths normally decline as trees age, but accelerated declines are evident in both ring-width series beginning about 1960. This effect appears as a decline in the ring-width indices.

ment did not occur at the same time for all trees at a given site. This is the same pattern described by JOHNSON and SIGGAMA.[9]

Tree-ring chronologies developed for the sites of greatest specimen replication are shown in Fig. 3. Low-frequency variance, mainly due to tree age and/or slowly varying ecological factors, has been removed from these series as described in the preceding section. However, ring-width series from all the sites still show a distinct tendency for consecutive negative values during the last two decades, although the growth-trend decline of spruce at the West Virginia site is most evident after 1970.

Figure 4 shows the July PDSIs for Virginia and West Virginia. These data demonstrate that the mid-1960s was a period of unusual drought in both states. This corresponds rather closely to the general time period for which substantial reductions in growth rates were first apparent for the trees cored in this study, thereby suggesting a possible relationship between drought stress and the pattern of growth-rate decline shown in Figs 2C, D, and 3.

The drought around 1930 was also associated with a growth-rate decline, but the trees recovered quickly (Figs 1–4). The magnitude of that drought was equal to, or greater than, the drought of the 1960s. This fact suggests that the recent growth-rate declines are not entirely due to drought, because the growth rate of most trees had not recovered from the recent decline by the time of sampling. Also, the West Virginia spruce showed evidence of already having recovered from the 1960s drought before the ring-width indices began to decrease again in the 1970s. Other potential contributing factors include various forms and effects of air pollution. However, duration of drought could also have been a factor because the more recent drought was characterized by negative values of July PDSI for more successive years.

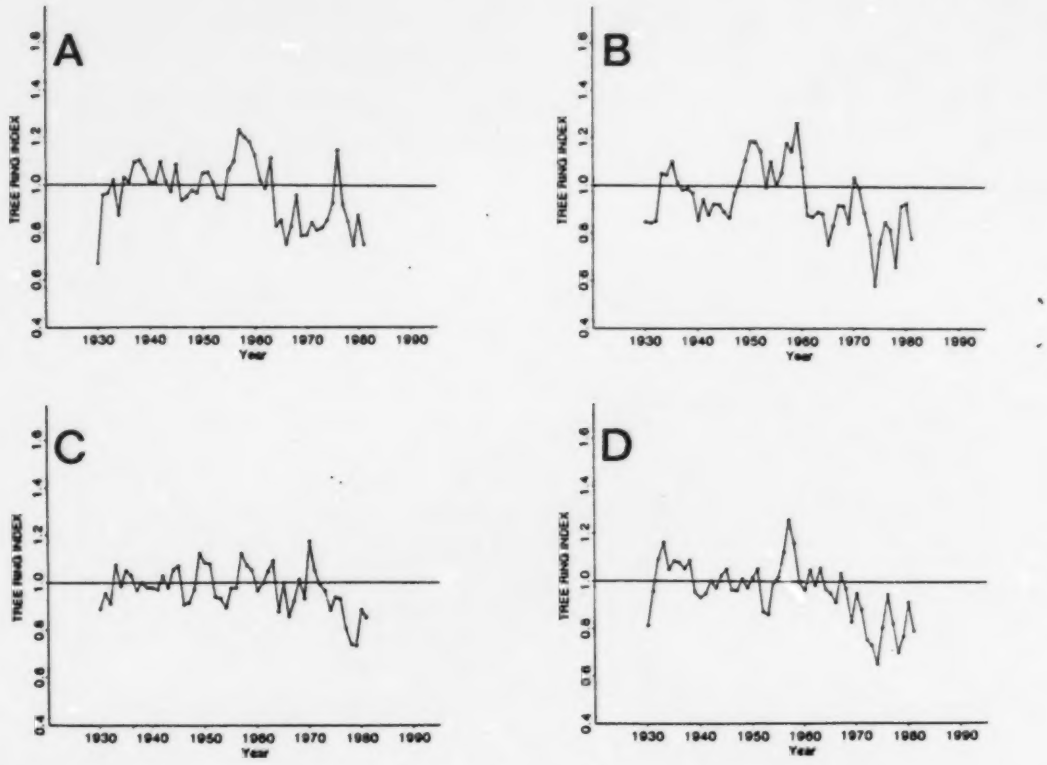

FIG. 3. Ring-width indices derived from the ring-width series shown in Fig. 1. (A) Red spruce in Highland County, VA. (B) Fraser fir at Mount Rogers, VA. (C) Red spruce in Randolph and Pocahontas counties, WV. (D) Balsam fir in Randolph and Pocahontas counties, WV.

To examine further the possibility that a climatic factor such as drought was responsible for the growth-rate declines, we performed a response-function analysis, as described in Methods, for each species at each of the four sites named in Figs 1 and 3. The residual (actual minus estimated) values represent the ring-width indices after those climatic effects that can be described by response-function analysis have been removed. These residuals, for each site, are plotted as in Fig. 5. The growth-rate declines are still evident, suggesting that they could not be explained via regression involving combinations of monthly climatic variables. Further, the decline in growth rate of spruce in West Virginia is not evident until after 1975. These particular trees apparently had recovered from any drought effects of the 1960s before beginning their recent growth-trend decline.

It is possible that linear regression failed to identify a climatic relationship that is present only in extreme cases but is weak or nonexistent in most cases considered in the regression. This case is termed a critical-value (or extreme-value) problem. A hypothetical example would be a case where only a PDSI of < -2 would affect tree growth. Because such values do not occur in most years, the regression analysis would not indicate that drought was, in general, a contributing factor to reduced rates of tree growth. Correlation

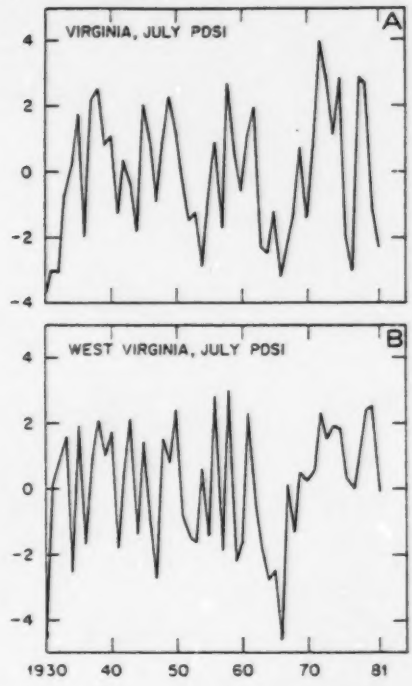

FIG. 4. July Palmer drought severity indices for (A) Virginia and (B) West Virginia.

coefficients between drought and ring-width indices might then be statistically indistinguishable from zero, as occurred in all cases when correlation coefficients between growing-season PDSIs and ring-width indices were calculated over the period 1930–1981. However, an extreme drought might trigger a growth-rate decline lasting several years. In such a case, the effects of drought would persist long after the drought has disappeared. That is, reduced growth rates in the 1970s might be due more to the drought in the 1960s than to the relatively 'unimportant' climatic fluctuations of the last 15 years. If that is so, then ring-width indices below the (1930–1981) average occurring together with the above-average drought indices during the 1970s (Fig. 4) would contribute negative crossproduct values to the correlation coefficient.

To illustrate further this point, we plotted the correlation coefficients between ring-width indices from the West Virginia fir chronology (the chronology shown in Fig. 3D) and corresponding PDSIs for overlapping 10-year periods from 1930–1939, 1931–1940, etc., to 1972–1981. These correlation coefficients are plotted in Fig. 6A. The obvious declines and sign changes represent the changing relationship between climate (drought) and tree growth rates over the period of analysis. For these fir, the large positive correlation coefficients for the periods beginning around 1958 represent the simultaneous decline of both the ring-width indices and PDSIs and an apparent temporary increase in the strength of the drought/tree-growth relationship as the drought index becomes anomalously low. The subsequent negative correlation coefficients occur when the downward trend in ring-width index continued during an upward trend in drought index as soil-moisture conditions improved but tree-growth rate did not. A single correlation coefficient calculated over the entire analysis period could not have resolved these features, nor would a single correlation coefficient centered on the period of growth-rate decline when the correlation between drought and ring-width index was changing most rapidly. The time-averaged correlation coefficient, like most of the individual 10-year correlation coefficients, was statistically indistinguishable from zero.

We calculated similar running 10-year correlation coefficients between West Virginia drought indices and the ring-width indices from the West Virginia spruce chronology. These correlation coefficients are shown in Fig. 6B. The spruce at this site (Fig. 3C) recovered somewhat after the drought peaked in 1966, and the unprecedented series of low ring-width index values did not begin until after 1970 when soil moisture had returned to normal levels. Thus, negative correlation coefficients become evident for periods beginning around 1970, reflecting the simultaneous occurrence of reduced ring-width indices and increased soil moisture. None of the correlation coefficients between drought index and ring-width index for the West Virginia spruce is statistically significant, however. Compared to the correlation coefficients for fir at the same site, the decline for spruce is delayed and diminished because the ring-width indices for these spruce showed a tendency to

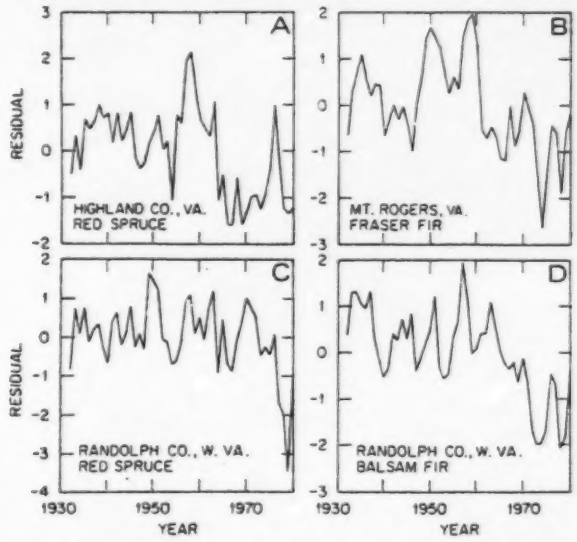

Fig. 5. Residual (actual minus estimated) ring-width chronology values, where the estimates were obtained by response-function analysis (regression of orthogonalized climatic variables) using as input data the monthly mean temperature and total precipitation values for 15 consecutive months ending with August of the year of ring formation. The residuals depict the ring-width chronology after any consistent linear climatic influences have been removed. Declines beginning at various times after the early 1960s are still evident in all chronologies.

recover as soil-moisture levels increased in the 1960s. Thus, it is difficult to attribute the recent decline in growth rate of these particular spruce to the drought of the 1960s. However, this does not rule out other climatic effects (e.g. involving winter temperature) that may not have been treated adequately by response-function analysis. Such effects may include time-lagged responses, threshold responses that only occur for a certain range of values of a climatic variable, or responses involving other complex relationships between climate and tree growth.

CONCLUSIONS

Climate (e.g. drought) cannot be ruled out as a contributing factor in the growth-rate decline of the trees in question. The temporal coincidence of severe drought with the growth-rate decline suggests that drought was at least partially responsible. However, most of the trees did not recover when the drought was followed by a moist period, suggesting the possibility of other effects such as air pollution/acid deposition or pathogen attacks. A drought-induced increase in susceptibility to such phenomena or other delayed effects of water stress (e.g. foliage loss) are also possibilities, but they are less likely in cases where the ring-width decline followed a rapid recovery from a previous drought, as in the case of the West Virginia spruce.

A definite link between acid deposition/air pollution and reduced rates of tree growth cannot be made on the basis of data presented in this paper. However, the possibility certainly exists that acid deposition/air pollution could be a

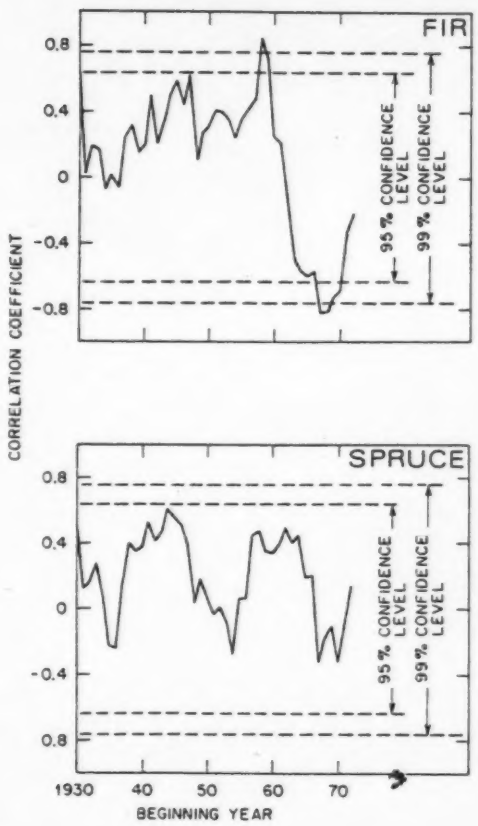

FIG. 6. Ten-year running correlation coefficients between state-average July Palmer drought severity index and ring-width index for fir (top), and spruce (bottom), from Randolph County, WV. The correlation coefficients were calculated for overlapping 10-year periods from 1930–1939, 1931–1940, etc., to 1972–1981, and plotted by beginning year. The maximum value for the fir chronology occurred for the period 1958–1967, when both the drought indices and the ring-width indices showed clear downward trends. The minimum value for the fir represents the 10-year period beginning in 1967, when the drought index began to return to normal but the ring-width index continued to decline before leveling off in the 1970s. For the spruce chronology, the decline in correlation coefficient is delayed and diminished because the most recent phase of the decline did not begin until the trees had apparently recovered somewhat from the drought that reached its maximum severity in 1966.

contributing factor in the observed growth-rate declines, and such a hypothesis has been suggested frequently in the recent literature.[9–11,18,19,26] The case for air pollution/acid deposition as a contributing factor to declines in growth rates of trees would be strengthened by documentation of one or more of the following situations. The first situation would involve the occurrence of unusual growth-rate declines where extreme climatic conditions (e.g. drought) did not occur simultaneously. Another situation would involve the occurrence of a climatic extreme in an area relatively free of air pollution where the trees either have been unaffected by the climate or the growth rate recovered quickly after the climate improved. The third situation would include the joint occurrence of severe climatic conditions and air pollution, but would also include the recorded occurrence of a past (pre-pollution) climatic extreme of a similar nature and of equal or greater magnitude that either was not related to a growth-rate decline or was followed by a rapid recovery of growth rate when the climate improved. The drought of the 1930s, apparent in Virginia and West Virginia, might provide such a case but it should be noted that drought is not necessarily the only climatic extreme that may affect tree growth. A greater knowledge of climatic and other influences on tree growth must be acquired before growth patterns can be conclusively shown to be either related to, or independent of, variations in air quality.

In any case, there is some evidence that a pattern of decline in tree-growth rate has occurred in mid-Appalachian subalpine coniferous forests similar to that reported for several sites in the northern Appalachians. In comparable forests of New York, Vermont, and New Hampshire, the decline in growth rates observed for red spruce has been accompanied by extensive and widespread mortality. Whether or not this is now occurring or is likely to occur in mid-Appalachian forests has yet to be determined. However, it is certainly plausible that continuation of whatever stress is adversely affecting these forests would ultimately result in widespread mortality of both spruce and fir. If such is the case, long-term successional changes could occur involving replacement of these species by other species more tolerant of stress factors involved.

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